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Fabrication of Thin-Film Fresnel Optics by Combining Diamond Turning and MEMS Techniques

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Abstract

A novel fabrication process was proposed for manufacturing thin-film metal Fresnel lenses for X-ray applications, which combines MEMS technologies and diamond turning technology. To prevent thin-film lens substrates from deflection during diamond turning, the thin films were prepared on single crystalline silicon wafers by electrolytic plating. After the Fresnel lens structure has been generated on the metal thin films by diamond turning, the backside supporting silicon substrate was selectively removed by reactive ion etching. Experimental results demonstrated that submicron level form accuracy and nanometer level surface roughness could be achieved by the proposed hybrid fabrication process.

Keywords: Micro structure; Fresnel lens; MEMS; ultraprecision cutting; diamond turning; optical elements

1. Introduction

In recent years, there is an increasing demand for thin film optics, such as X-ray Fresnel lenses, in advanced optical systems like space observation satellites [1, 2]. This is because the conventional reflecting optics has insufficient angular resolution and sensitivity, and is difficult to operate high energy short wavelength rays. To use thin film diffractive and Fresnel optics, extremely high angular resolution (~1µsec) can be realized which enables operating high energy hard X-ray and γ–ray. For this reason, thin-film Fresnel lenses made of metal materials, such as copper (which has high permeability and high refraction index for X-ray), are required.

However, to fabricate thin film optics on soft metal materials by mechanical machining is extremely difficult, because a thin film substrate is very easy to be deflected during clamping and machining due to external forces. To solve the workpiece deflection problem, in this study we proposed to fabricate thin film optics by combining diamond turning and micro electromechanical system (MEMS) techniques. Key steps of the proposed process will be described in detail and preliminary fabrication experiments for a miniature model copper Fresnel lens for X-ray applications will be shown.

2. Experimental

2.1. Process steps

As a test piece, a Fresnel lens having a thickness of 10 µm was fabricated on copper substrate. The designed shape of the Fresnel lens is schematically shown in Fig.1. The diameter of the lens substrate is 20 mm and that of the effective Fresnel lens area is 2.8 mm. The designed height of the Fresnel zone step is 6.3 µm. To fabricate the thin film Fresnel lens, a hybrid process involving diamond turning and MEMS techniques was adopted.

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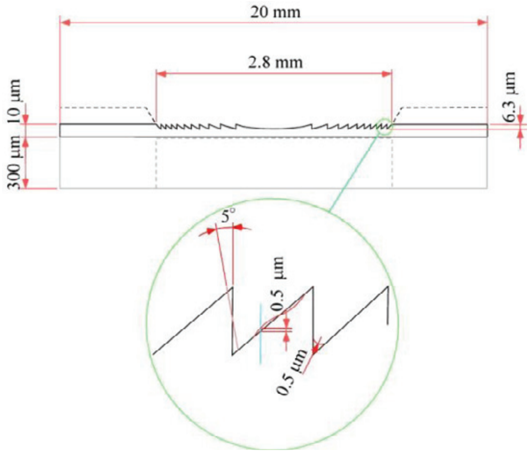


Fig.1 Schematic diagram of thin film Fresnel lens

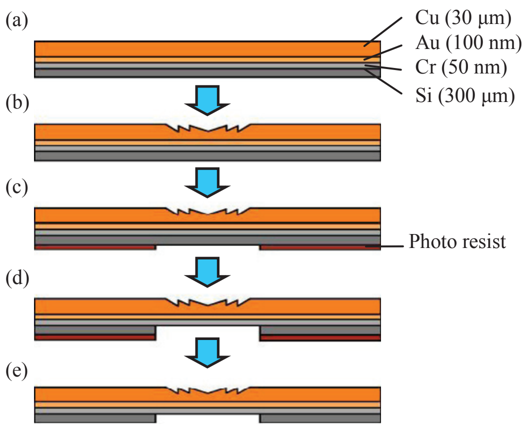


Fig.2 Flow chart of the hybrid fabrication process

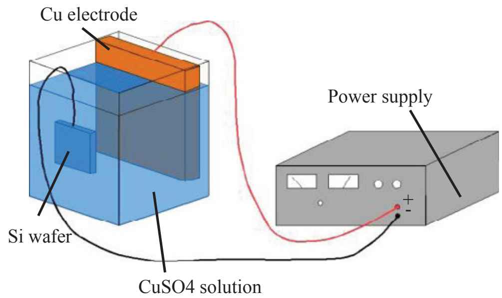


Fig.3 Schematic diagram of electrolytic plating setup

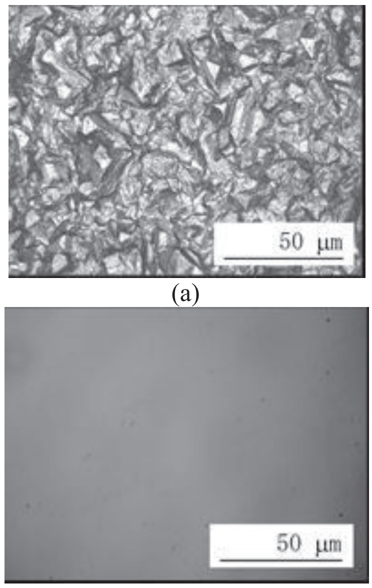


Fig.4 SEM micrographs of (a) plated Cu surface and (b) face turned surface.

The flow chart of the hybrid fabrication process is schematically shown in Fig.2. The process contains the following main steps: (a) Spattering thin films of Cr (50 nm thick) and Au (100 nm thick) on a silicon wafer, which act as interlayers for electrolytic plating of Cu (30 μm thick); (b) Diamond turning of the Cu layer for the Fresnel lens structure; (c) Spin coating of a photoresist layer on the backside of the silicon wafer, and removing the central region of the photoresist layer which corresponds to the Fresnel lens region by photolithography; (d) Removing the exposed silicon substrate material by reactive ion etching (RIE); (e) Removing the residual photoresist layer by chemical etching and obtaining a thin film Fresnel lens on Cu.

In step (a), sputtering of Cr and Au thin films were performed by high frequency multi-sputtering equipment JEOL JEC-SP360R. The RF power was 300 W, and the pressure used was 3×10^{-3} Pa. It should be noted that the Cr and Au interlayers were not removed after the lens has been fabricated, since they do not affect the optical performance of the copper Fresnel lens.

Electrolytic plating of Cu was performed using an electrolytic plating setup as shown in Fig.3. Plating was performed in a $CuSO_4$ solution which has a pH value of 1.8. The electrical current was 40mA, and the time for plating was 6 h. This condition leads to a plating thickness of ~30 μm. As the plated surface was quite rough, face turning was performed before machining the Fresnel structure. Fig.4 shows SEM micrographs of a plated surface and a face turned surface. The step (b), namely, diamond turning of Fresnel lens structure, will be described in detail in the next section.

In step (c), mask aligner MA6 (SUSS Microtech) was used for photolithography. Photoresists OAP and PMER were spin coated at 500 rpm for 5 sec and 2000rpm for 20 sec. The prebaking time was 5 min at 90°C and 5 min at 110°C. The developer was P-7G and developing time was 6 min. In step (d), an inductive coupled plasma RIE (ICP-RIE) system was used to remove silicon on the back of the Fresnel lens. In step (e), acetone was used to remove the residual photoresist.

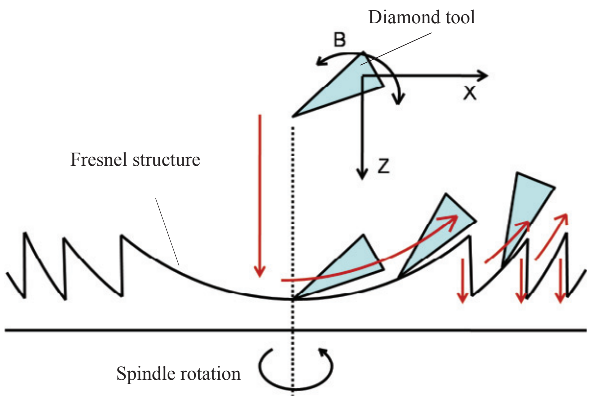


Fig.5 Schematic model for Fresnel structure cutting

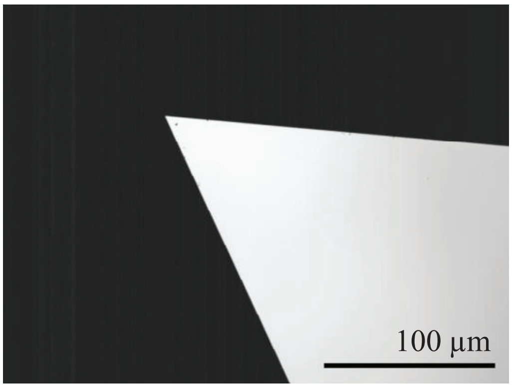


Fig.6 SEM micrograph of diamond tool tip

Table 1 Diamond turning conditions

Workpiece	Cu plating (thickness 30 μm)
Lens diameter	20 mm (Fresnel area 2.8 mm)
Zone depth	6.3 μm
Tool included angle	60°
Tool rake angle	0°
Tool relief angle	10°
Feed rate	0.05 μm/rev
Spindle rotational rate	2000 rpm
Cutting fluid	Kerosene mist

2.2. Diamond turning

To generate the Fresnel structure on the Cu layer, in step (b) of Fig.2, diamond turning tests were performed. The schematic model of the Fresnel structure machining is shown in Fig.5. An extremely sharpened single crystalline diamond tool is numerically controlled under three-axis (XZB) simultaneous control [3]. The tool is fed from the center to the outer region of the workpiece which is rotated by an air spindle. The machining operation for a Fresnel zone consists of two steps. First, the tool moves along the Z axis, namely the vertical axis, to generate the cylindrical surface of the zone step. Next, the tool moves and at the same time rotates under XZB three-axis control to generate the curved surface.

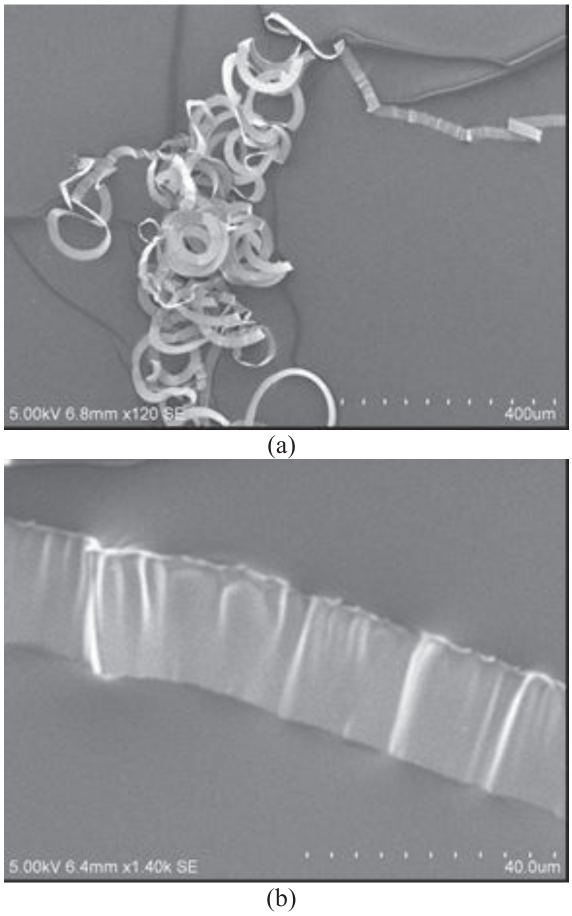
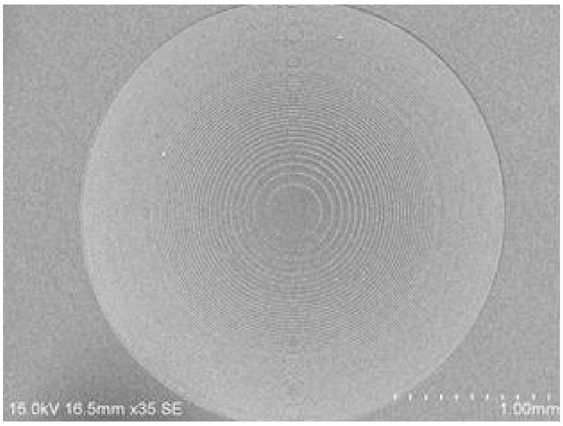


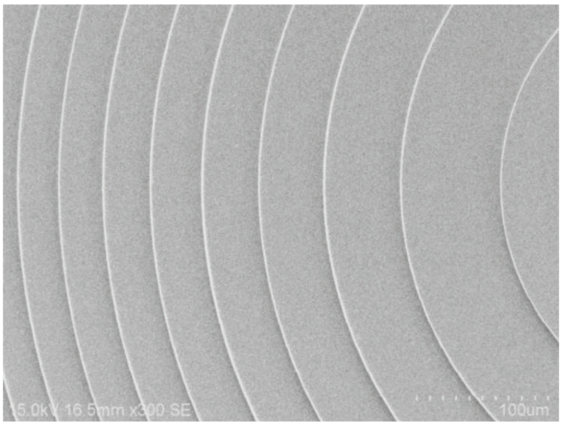
Fig.7 SEM micrographs of cutting chips: (a) low magnification view and (b) high magnification view.

In the experiments, an ultraprecision diamond turning machine NACHI-ASP15 was used. The machine has an ultraprecision air-bearing spindle, two perpendicular linear tables (X- and Z-axes) and a rotary table (B-axis). The linear tables are supported by high-stiffness hydrostatic bearings and are driven by servomotors via hydrostatic screws with negligible mechanical friction. The rotary table is also supported by hydrostatic bearings and driven by a friction drive in order to prevent from backlash movements. Laser hologram scales are used to accurately position all these tables. After a renovation of the numerical feedback control system of the machine, the linear tables can be moved at 1 nm per step and the rotary table can be rotated with an angular resolution of 0.00001°. To isolate the lathe from environmental vibration, the main section of the machine was fixed to a granite bed, which is supported by a set of air mounts.

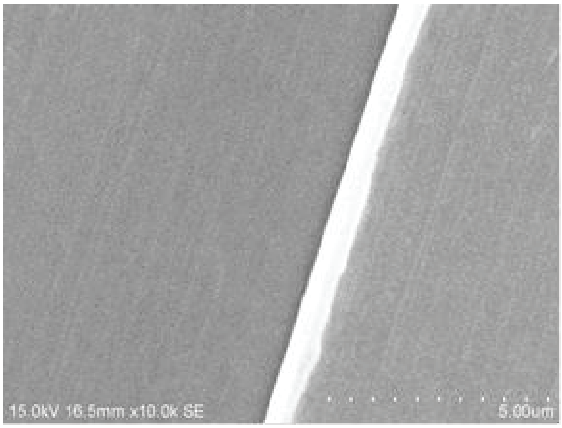
Two single crystalline diamond tools were used. The one used for face turning was a round nosed tool having a nose radius of 2 mm, a rake angle of 0° and a relief angle of 6°. In face turning, depth of cut was 10 μm, and feed rate was 5 μm /rev at a spindle speed of 1000 rpm.



(a)



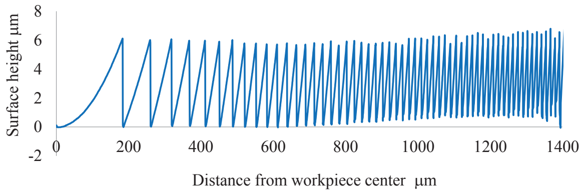
(b)



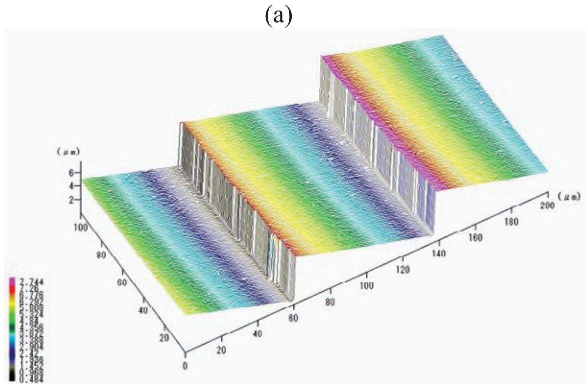
(c)

Fig.8 SEM micrographs of machined lens surface: (a) overall view, (b) Fresnel zones, and (c) a zone step.

The tool used for generating Fresnel structure was a V-shaped tool which has an included angle of 60°. The SEM micrograph of the tool tip is shown in Fig.6. The cutting edge angle of the tool was adjusted and controlled using the B-axis rotary table of the lathe. The experimental conditions are listed in Table 1.



(a)



(b)

Fig.9 Fresnel lens form accuracy measurement results: (a) two-dimensional cross-sectional profile, (b) three-dimensional topography of a section of lens surface.

A noncontact three-directional measuring machine, Mitaka NH-3SP, was used to measure the lens accuracy, and a scanning electron microscope (SEM) was used to observe the machined surface and cutting chips.

3. Results and discussion

3.1. Chip formation

Fig.7 shows SEM micrographs of cutting chips collected during diamond turning of the Fresnel structure. The chips are in the form of slightly curled ribbons. The width and thickness of the ribbons are very uniform, indicating that the cutting process was stable.

3.2. Lens surface

Fig.8 shows SEM micrographs of the machined lens surface. In Figs. 8 (a) and (b), it can be seen that the concentric Fresnel zones are clearly generated and the lens surface are extremely smooth. In Fig.8 (c), we can see that the zone step (height ~6.3 µm) is very straight and flat, where no burr formation was seen. This result indicates that the diamond turning conditions used in the experiments were suitable. The surface roughness of the Fresnel lens surface measured by the noncontact three-directional measuring machine Mitaka NH-3SP is 2 nm Ra (15nmRy).

3.3. Form accuracy

The surface topography of the fabricated Fresnel lens was evaluated by the noncontact three-directional measuring machine Mitaka NH-3SP, and typical results are shown in Fig.9. The lens form accuracy is in the submicron level, which meets the designed requirements of the Fresnel lens.

4. Conclusions

A miniature model of a thin film metal Fresnel lens for hard X-ray applications has been fabricated by combining diamond turning and MEMS techniques involving sputtering, electrolytic plating, reactive ion etching, and photolithography. The proposed method effectively solved the problem of deflection in thin film lens substrates. The preliminary results show that submicron level form accuracy and nanometer level surface roughness can be successfully achieved by the proposed hybrid fabrication process.

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